

Possible pentaquarks with heavy quarks

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Inspired by the discovery of two pentaquarks $P_c(4380)$ and $P_c(4450)$ at the LHCb detector, we study possible hidden-charm molecular pentaquarks composed of an anti-charmed meson and a charmed baryon in the framework of quark delocalization color screening model. Our results suggest that $P_c(4380)$ is a mixed structure of $\Lambda_c D^*$, $\Sigma_c D^*$, $\Sigma_c^* D$, and $\Sigma_c^* D^*$ with quantum numbers $IJ^P = \frac{1}{2} \frac{3}{2}^-$, and the main channel is $\Sigma_c^* D$; $P_c(4450)$ can be interpreted as the $\Sigma_c^* D^*$ state of $IJ^P = \frac{1}{2} \frac{5}{2}^-$. We also obtain another bound state $\Sigma_c D$ with quantum numbers of $IJ^P = \frac{1}{2} \frac{1}{2}^-$ and a mass of $4286.4 \sim 4301.7(\text{MeV})$. The corresponding system of hidden-bottom pentaquarks has the similar properties as that of hidden-charm pentaquarks system. These partners of $P_c(4380)$ and $P_c(4450)$ are worth searching in the future experiment.

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I. INTRODUCTION

Multiquark states were studied even before the advent of quantum chromodynamics (QCD). The development of QCD accelerated multiquark studies because it is natural in QCD that there should be multiquark states, including glueballs and quark-gluon hybrids. After more than 40 years of quark model study, the idea about baryon and meson is about to go beyond the naive picture: baryon q^3 and meson $q\bar{q}$. The proton spin puzzle could be explained by introducing the $q^3 q\bar{q}$ component in the quark model [1]. In order to understand the baryon spectroscopy better, the five-quark component of proton was proposed [2]. The baryon resonance is certainly coupled to the meson-baryon scattering state and should be studied by coupling the q^3 with $q^3 q\bar{q}$ scattering channel in a quark model approach. Although the strange pentaquark states claimed by experimental groups few years ago might be questionable (LEPS collaboration insists on the existence of pentaquark Θ^+ [3]) and the multiquark states might be hard to be identified, the multiquark study is indispensable for understanding the low energy quantum chromodynamics (QCD), because the multi-quark states can provide information unavailable for $q\bar{q}$ meson and q^3 baryon, especially the property of hidden color structure.

In the past decade, many near-threshold charmonium-like states have been observed at BESIII, Belle, BaBar, and LHCb, triggering lots of studies on the molecule-like hadrons containing heavy quark. In the heavy quark sector, the large masses of the heavy baryons reduce the kinetic of the system, which makes it easier to form bound states. So the heavy quarks play an important role to stabilize the multiquark systems. There were many theoret-

ical studies of hidden-charm pentaquarks [4–7], especially the prediction of narrow N^* and Λ^* resonances with hidden charm above 4 GeV by using the coupled-channel unitary approach [4], and the systematical investigation of possible hidden-charm molecular baryons with components of an anti-charmed meson and a charmed baryon within the one boson exchange model [5].

Very recently, the LHCb Collaboration observed two pentaquark-charmonium states in the $J/\psi p$ invariant mass spectrum of $\Lambda_b^0 \rightarrow J/\psi K^- p$ [8]. One is $P_c(4380)$ with a mass of $4380 \pm 8 \pm 29$ MeV and a width of $205 \pm 18 \pm 86$ MeV, and another one is $P_c(4450)$ with a mass of $4449.8 \pm 1.7 \pm 2.5$ MeV and a width of $39 \pm 5 \pm 19$ MeV. The preferred J^P assignments are of opposite parity, with one state having spin $\frac{3}{2}$ and the other $\frac{5}{2}$. Then, a lot of theoretical work have been done to explain these two states. In Ref. [9], they interpreted these two hidden-charm states as the loosely bound $\Sigma_c(2455)D^*$ and $\Sigma_c^*(2520)D^*$ molecular states by using the boson exchange interaction model, and gave the spin parity $J^P = \frac{3}{2}^-$ and $\frac{5}{2}^-$, respectively. While in Ref. [10], a Bethe-Salpeter equation approach was used to studied the $\bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c$ interactions, and then $P_c(4380)$ and $P_c(4450)$ were identified as $\bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c$ molecular states with the spin parity $J^P = \frac{3}{2}^-$ and $\frac{5}{2}^+$, respectively. A QCD sum rule investigation was performed, by which the $P_c(4380)$ was suggested as a $\bar{D}^*\Sigma_c$ hidden-charm pentaquark with $J^P = \frac{3}{2}^-$ and the $P_c(4450)$ was proposed as a mixed hidden-charm pentaquark of $\bar{D}^*\Lambda_c$ and $\bar{D}^*\Sigma_c$ with $J^P = \frac{5}{2}^+$ [11]. Also a coupled-channel calculation was performed to analyze the $\Lambda_b^0 \rightarrow J/\psi K^- p$ reaction and gave support to a $J^P = \frac{3}{2}^-$ assignment to the $P_c(4450)$ and to its nature as a molecular state mostly made of $\bar{D}^*\Sigma_c$ and $\bar{D}^*\Sigma_c^*$ [12]. Thus, different models may give different descriptions for the resonance structures. Clearly the quark level study of these two pentaquark-charmonium states is interesting and neces-

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sary.

It is well known that the forces between nucleons (hadronic clusters of quarks) are qualitative similar to the forces between atoms (molecular force). This molecular model of nuclear forces, quark delocalization color screening model (QDCSM) [13], has been developed and extensively studied. In this model, quarks confined in one nucleon are allowed to delocalize to a nearby baryon and the confinement interaction between quarks in different baryon orbits is modified to include a color screening factor. The latter is a model description of the hidden color channel coupling effect [14]. The delocalization parameter is determined by the dynamics of the interacting quark system, thus allows the quark system to choose the most favorable configuration through its own dynamics in a larger Hilbert space. The model gives a good description of NN and YN interactions and the properties of deuteron [15]. It is also employed to calculate the baryon-baryon scattering phase shifts in the framework of the resonating group method (RGM), and the dibaryon candidates are also studied with this model [16, 17].

In this work, we study the interactions of possible hidden-charm molecular pentaquarks with components

of an anti-charmed meson and a charmed baryon in QDCSM, and the channel-coupling effect are considered. Our purpose is to understand the interaction properties of an anti-charmed meson and a charmed baryon and to see whether there are any hidden-charm pentaquark bound states or resonances. Extension of the study to the bottom case is also interesting, so we also investigate hidden-bottom pentaquark systems in the present work. The structure of this paper is as follows. After the introduction, we present a brief introduction of the quark model used in section II. Section III devotes to the numerical results and discussions. The summary is shown in the last section.

II. THE QUARK DELOCALIZATION COLOR SCREENING MODEL (QDCSM)

The detail of QDCSM used in the present work can be found in the references [13–17]. Here, we just present the salient features of the model. The model Hamiltonian is:

$$\begin{aligned}
 H &= \sum_{i=1}^6 \left(m_i + \frac{p_i^2}{2m_i} \right) - T_c + \sum_{i < j} [V^G(r_{ij}) + V^\chi(r_{ij}) + V^C(r_{ij})], \\
 V^G(r_{ij}) &= \frac{1}{4} \alpha_s \lambda_i \cdot \lambda_j \left[\frac{1}{r_{ij}} - \frac{\pi}{2} \left(\frac{1}{m_i^2} + \frac{1}{m_j^2} + \frac{4\sigma_i \cdot \sigma_j}{3m_i m_j} \right) \delta(r_{ij}) - \frac{3}{4m_i m_j r_{ij}^3} S_{ij} \right], \\
 V^\chi(r_{ij}) &= \frac{1}{3} \alpha_{ch} \frac{\Lambda^2}{\Lambda^2 - m_\chi^2} m_\chi \left\{ \left[Y(m_\chi r_{ij}) - \frac{\Lambda^3}{m_\chi^3} Y(\Lambda r_{ij}) \right] \sigma_i \cdot \sigma_j \right. \\
 &\quad \left. + \left[H(m_\chi r_{ij}) - \frac{\Lambda^3}{m_\chi^3} H(\Lambda r_{ij}) \right] S_{ij} \right\} \mathbf{F}_i \cdot \mathbf{F}_j, \quad \chi = \pi, K, \eta \\
 V^C(r_{ij}) &= -a_c \lambda_i \cdot \lambda_j [f(r_{ij}) + V_0], \\
 f(r_{ij}) &= \begin{cases} r_{ij}^2 & \text{if } i, j \text{ occur in the same baryon orbit} \\ \frac{1 - e^{-\mu_{ij} r_{ij}^2}}{\mu_{ij}} & \text{if } i, j \text{ occur in different baryon orbits} \end{cases} \\
 S_{ij} &= \frac{(\sigma_i \cdot \mathbf{r}_{ij})(\sigma_j \cdot \mathbf{r}_{ij})}{r_{ij}^2} - \frac{1}{3} \sigma_i \cdot \sigma_j.
 \end{aligned} \tag{1}$$

Where S_{ij} is quark tensor operator; $Y(x)$ and $H(x)$ are standard Yukawa functions [18]; T_c is the kinetic energy of the center of mass; α_{ch} is the chiral coupling constant; determined as usual from the π -nucleon coupling constant; α_s is the quark-gluon coupling constant. In order to cover the wide energy range from light to heavy quarks one introduces an effective scale-dependent quark-gluon coupling $\alpha_s(\mu)$ [19]:

$$\alpha_s(\mu) = \frac{\alpha_0}{\ln\left(\frac{\mu^2 + \mu_0^2}{\Lambda_0^2}\right)}, \tag{2}$$

where μ is the reduced mass of two interacting quarks. All other symbols have their usual meanings. Here, a phenomenological color screening confinement potential is used, and μ_{ij} is the color screening parameter. For the light-flavor quark system, it is determined by fitting the deuteron properties, NN scattering phase shifts, $N\Lambda$ and $N\Sigma$ scattering phase shifts, respectively, with $\mu_{uu} = 0.45$, $\mu_{us} = 0.19$ and $\mu_{ss} = 0.08$, satisfying the relation, $\mu_{us}^2 = \mu_{uu} * \mu_{ss}$. When extending to the heavy quark case, there is no experimental data available, so we take

it as a adjustable parameter. In the present work, we take $\mu_{cc} = 0.01 \sim 0.0001 \text{ fm}^{-2}$ and μ_{uc} is obtained by the relation $\mu_{uc}^2 = \mu_{uu} * \mu_{cc}$. All other parameters are also taken from our previous work [17], except for the charm and bottom quark masses m_c and m_b , which are fixed by a fitting to the masses of the charmed and bottom baryons and mesons. The values of those parameters are listed in Table I. The calculated masses of the charmed and bottom baryons and mesons are shown in Table II.

The quark delocalization in QDCSM is realized by specifying the single particle orbital wave function of QDCSM as a linear combination of left and right Gaussians, the single particle orbital wave functions used in the ordinary quark cluster model,

$$\begin{aligned}\psi_\alpha(\mathbf{s}_i, \epsilon) &= (\phi_\alpha(\mathbf{s}_i) + \epsilon \phi_\alpha(-\mathbf{s}_i)) / N(\epsilon), \\ \psi_\beta(-\mathbf{s}_i, \epsilon) &= (\phi_\beta(-\mathbf{s}_i) + \epsilon \phi_\beta(\mathbf{s}_i)) / N(\epsilon), \\ N(\epsilon) &= \sqrt{1 + \epsilon^2 + 2\epsilon e^{-s_i^2/4b^2}}, \\ \phi_\alpha(\mathbf{s}_i) &= \left(\frac{1}{\pi b^2}\right)^{3/4} e^{-\frac{1}{2b^2}(\mathbf{r}_\alpha - \mathbf{s}_i/2)^2} \\ \phi_\beta(-\mathbf{s}_i) &= \left(\frac{1}{\pi b^2}\right)^{3/4} e^{-\frac{1}{2b^2}(\mathbf{r}_\beta + \mathbf{s}_i/2)^2}.\end{aligned}\quad (3)$$

Here \mathbf{s}_i , $i = 1, 2, \dots, n$ are the generator coordinates, which are introduced to expand the relative motion wavefunction [14]. The mixing parameter $\epsilon(\mathbf{s}_i)$ is not an adjusted one but determined variationally by the dynamics of the multi-quark system itself. This assumption allows the multi-quark system to choose its favorable configuration in the interacting process. It has been used to explain the cross-over transition between hadron phase and quark-gluon plasma phase [21].

III. THE RESULTS AND DISCUSSIONS

It looks natural to study $P_c(4380)$ and $P_c(4450)$ in $J/\psi N$ structure, since these two states were observed in the $J/\psi p$ invariant mass spectrum. However, the masses of these observed $P_c(4380)$ and $P_c(4450)$ are significantly larger than the threshold of J/ψ and N , but close to the thresholds of D/D^* and $\Lambda_c/\Sigma_c/\Sigma_c^*$. Therefore, we investigate the possible hidden-charm molecular pentaquarks composed of an anti-charmed meson and a charmed baryon, with $Y = 1$, $I = \frac{1}{2}$ and $\frac{3}{2}$, $J^P = \frac{1}{2}^-$, $\frac{3}{2}^-$, and $\frac{5}{2}^-$. All the channels involved are listed in Table III. The channel coupling effects are also considered in our calculation.

First, the effective potentials between D/D^* and $\Lambda_c/\Sigma_c/\Sigma_c^*$ are calculated and shown in Figs. 1-4, because an attractive potential is necessary for forming a bound state or resonance. The effective potential between two colorless clusters is defined as, $V(s) = E(s) - E(\infty)$, where $E(s)$ is the energy of the system at the separation s of two clusters. The adiabatic approximation is used to obtain the energy of the system. As mentioned

in Sec. II, a phenomenological color screening confinement potential is introduced in our model. For the multi-quark systems with heavy quark, because no experimental data is available, so we take three different values of μ_{cc} ($\mu_{cc} = 0.01, 0.001, 0.0001$), to test the dependence of our results on this parameter.

For the $IJ^P = \frac{1}{2}\frac{1}{2}^-$ system (Fig. 1), one sees that the potentials are all attractive for the channels $\Sigma_c D$, $\Sigma_c D^*$ and $\Sigma_c^* D^*$. While for the channels $\Lambda_c D$ and $\Lambda_c D^*$, the potentials are repulsive and so no bound states can be formed in these two channels. The attraction between Σ_c^* and D^* is the largest one, followed by that of the $\Sigma_c D^*$ channel, which is a little larger than that of the $\Sigma_c D$ channel. Comparing figures (a), (b) and (c) in Fig. 1, we also find that larger values of μ_{cc} give rise to deeper attractions for the attractive channels, although the variation is not very significant. However, for the repulsive $\Lambda_c D$ and $\Lambda_c D^*$ channels, the potentials are quantitatively the same with three different values of μ_{cc} .

For the $IJ^P = \frac{1}{2}\frac{3}{2}^-$ system (Fig. 2), similar results as that of $IJ^P = \frac{1}{2}\frac{1}{2}^-$ system are obtained. The potentials are all attractive for channels $\Sigma_c D^*$, $\Sigma_c^* D$ and $\Sigma_c^* D^*$, while for the $\Lambda_c D^*$ channel, it is strongly repulsive. For the dependence of potentials on the different values of μ_{cc} , the behavior is the same as that for the $IJ^P = \frac{1}{2}\frac{1}{2}^-$ system.

For the $IJ^P = \frac{1}{2}\frac{5}{2}^-$ system (Fig. 3), there is only one channel $\Sigma_c^* D^*$, the potentials are attractive, which are similar with that in $IJ^P = \frac{1}{2}\frac{1}{2}^-$ and $IJ^P = \frac{1}{2}\frac{3}{2}^-$ system.

For the $I = \frac{3}{2}$ system, since the differences are not very obvious with three values of μ_{cc} , to save the space, we only show the potentials of $\mu_{cc} = 0.01$ here. The effective potentials of $J^P = \frac{1}{2}^-$, $\frac{3}{2}^-$, and $\frac{5}{2}^-$ are shown in Fig. 4(a), (b) and (c), respectively. From Fig. 4(a), we can see that the potentials are attractive for the $J^P = \frac{1}{2}^-$ channels $\Sigma_c D^*$ and $\Sigma_c^* D^*$, but the attractions are very weak. While for the channel $\Sigma_c D$, the potential is repulsive and so no bound state can be formed in this single channel. For the $J^P = \frac{3}{2}^-$ and $\frac{5}{2}^-$ system shown in Fig. 4(b) and (c), the potentials of all channels are repulsive.

In order to see whether or not there is any bound state, a dynamic calculation is needed. The resonating group method (RGM), described in more detail in Ref.[22], is used here. Expanding the relative motion wavefunction between two clusters in the RGM equation by gaussians, the integro-differential equation of RGM can be reduced to algebraic equation, the generalized eigen-equation. The energy of the system can be obtained by solving the eigen-equation. In the calculation, the baryon-meson separation ($|\mathbf{s}_n|$) is taken to be less than 6 fm (to keep the matrix dimension manageably small).

For the $IJ^P = \frac{1}{2}\frac{1}{2}^-$ system, the single channel calculation shows that both $\Lambda_c D$ and $\Lambda_c D^*$ are unbound. This

TABLE I: Model parameters discussed in this paper: $m_\pi = 0.7 \text{ fm}^{-1}$, $m_k = 2.51 \text{ fm}^{-1}$, $m_\eta = 2.77 \text{ fm}^{-1}$, $\Lambda_\pi = 4.2 \text{ fm}^{-1}$, $\Lambda_k = 5.2 \text{ fm}^{-1}$, $\Lambda_\eta = 5.2 \text{ fm}^{-1}$, $\alpha_{ch} = 0.027$.

$b(\text{fm})$	$m_s(\text{MeV})$	$m_c(\text{MeV})$	$m_b(\text{MeV})$	$a_c(\text{MeV fm}^{-2})$	$V_0(\text{MeV})$	α_0	$\Lambda_0(\text{fm}^{-1})$	$u_0(\text{MeV})$
0.518	573	1700	5140	58.03	-1.2883	0.5101	1.525	445.808

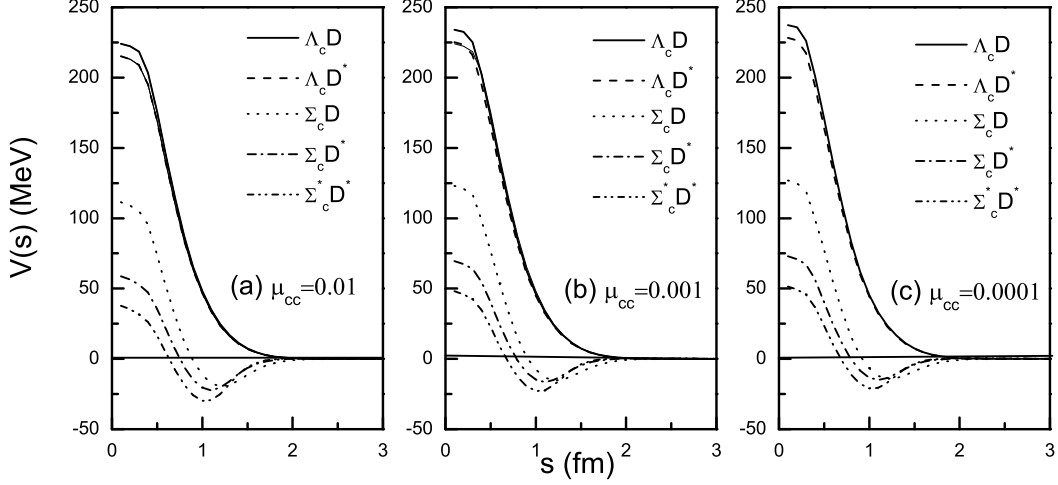


FIG. 1: The potentials of different channels for the $IJ^P = \frac{1}{2} \frac{1}{2}^-$ system.

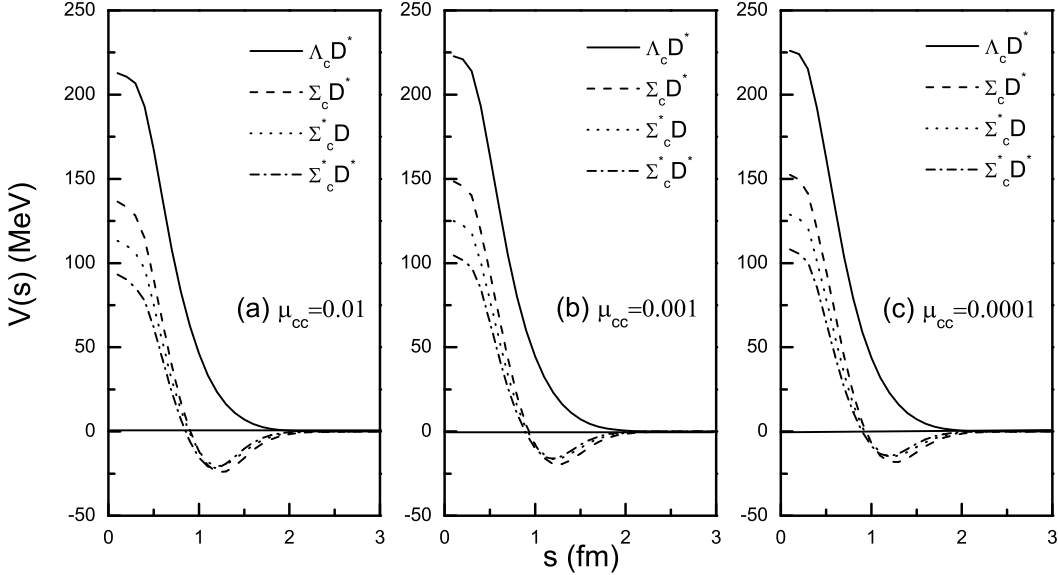


FIG. 2: The potentials of different channels for the $IJ^P = \frac{1}{2} \frac{3}{2}^-$ system.

is reasonable, because the interaction of these two channels are repulsive as mentioned above. While, due to the attractions, the energies of $\Sigma_c D$, $\Sigma_c D^*$ and $\Sigma_c^* D^*$ are below their corresponding thresholds. The binding energy of these three states are listed in Table IV, in which 'ub' means unbound. Here we should mention how we obtain the mass of a hidden-charm molecular pentaquark. Generally, we can use the function of $M = M_1 + M_2 + B$ to calculate the mass of a molecular pentaquark, where M_1 and M_2 stand for the mass of a charmed baryon and an anti-charmed meson respectively, and B is the binding energy

of this molecular state. Take the state $\Sigma_c D$ for example, $M = 2377.6 + 1889.7 + (-18.1) = 4249.2 \text{ (MeV)}$. Obviously, the masses of Σ_c and D used here are theoretical values but not the experimental data. In order to compare our results to the experimental data, we do a mass shift here by using the experimental values of charmed baryons and anti-charmed mesons. Finally, we obtain the mass of $\Sigma_c D$ by $M = 2455.0 + 1864.0 + (-18.1) = 4300.9 \text{ (MeV)}$. So in our quark model calculation, for the $IJ^P = \frac{1}{2} \frac{1}{2}^-$, $M_{\Sigma_c D} = 4300.9 \sim 4309.1 \text{ MeV}$, $M_{\Sigma_c D^*} = 4441.4 \sim 4444.1 \text{ MeV}$, $M_{\Sigma_c^* D^*} = 4503.1 \sim 4509.7 \text{ MeV}$.

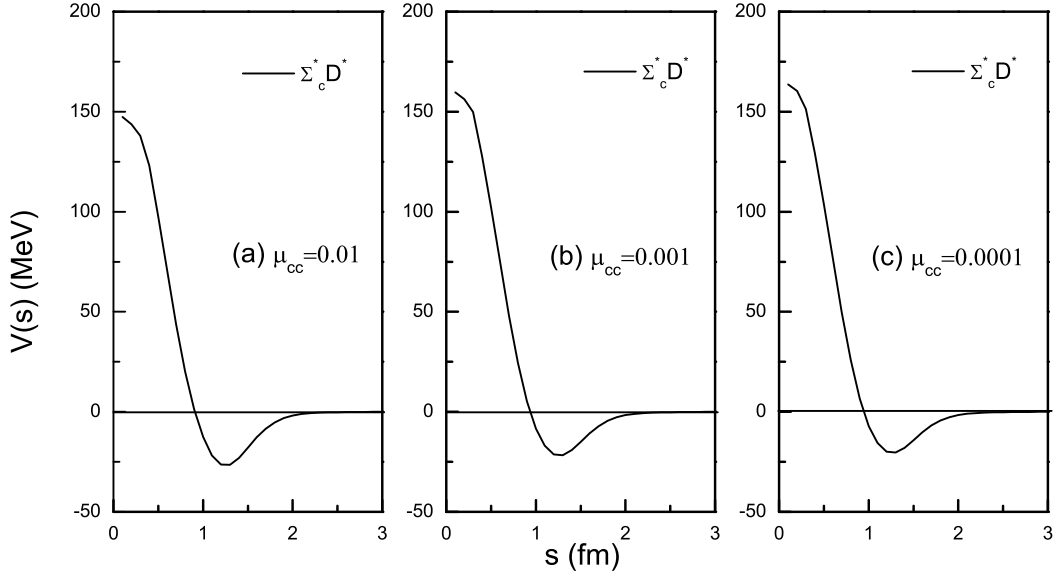


FIG. 3: The potential of a single channel for the $IJ^P = \frac{1}{2} \frac{5}{2}^-$ system.

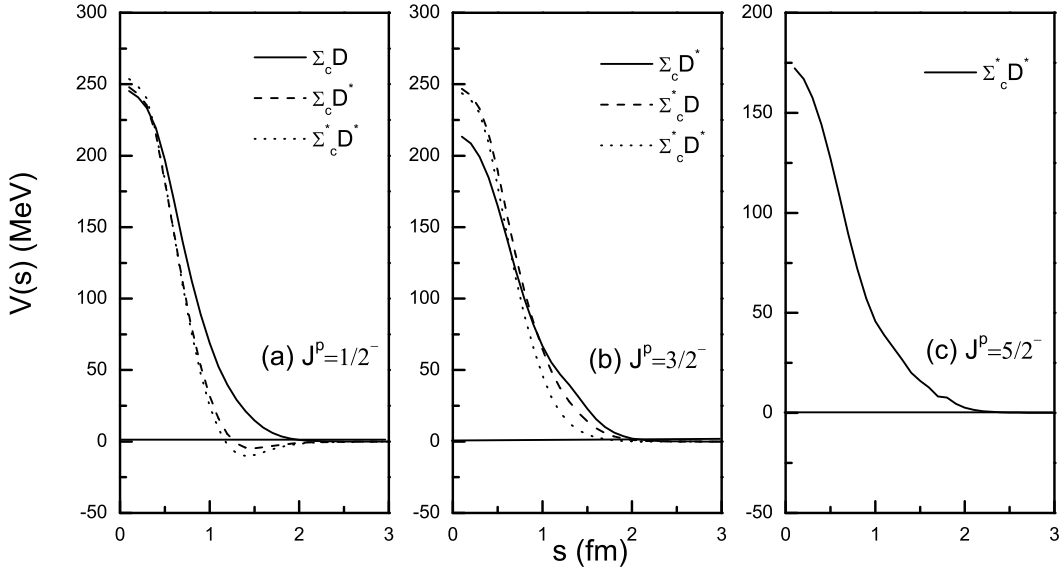


FIG. 4: The potentials of different channels for the $I = \frac{3}{2}$ system with $\mu_{cc} = 0.01$.

These results are qualitatively similar with the conclusion of Ref.[4], in which they predicted two new N^* states (the $\Sigma_c D$ molecular state $N^*(4265)$ and the $\Sigma_c D^*$ molecular state $N^*(4415)$) by the coupled-channel unitary approach.

At the same time, we also do a channel-coupling calculation and a bound state is obtained. The binding energy is also shown in Table IV under the head '5cc.', and the mass of the bound state is shown in Table V. In Table V, we also illustrate the ratios of all channels coupled, from which we can judge the main state of a hidden-charm molecular pentaquark. It is obvious in Table V that the main state of the $IJ^P = \frac{1}{2} \frac{1}{2}^-$ system is $\Sigma_c D$, with the ratio 74.3% \sim 80%. Moreover, the mass of this $IJ^P = \frac{1}{2} \frac{1}{2}^-$ system is 4286.4 \sim 4301.7 (MeV). Besides, the ratio of

$\Lambda_c D$ is very small, only 0.4% \sim 0.8%, which means the coupling effect of $\Lambda_c D$ is ignorable, although it is through the central force. This result is similar with the conclusion of Ref.[23], in which they obtained a $IS = \frac{1}{2} \frac{1}{2}^-$ $\Sigma_c D$ bound state in the chiral quark model with the energy of about 4279 \sim 4316 (MeV), and the effect of Λ_c channel is also negligible. Finally, because the $\Sigma_c D$ can be coupled to $N\eta_c$ and $J/\psi p$, and the channel coupling will shift the energy of the state, a further work is needed to check whether the state $\Sigma_c D$ can survive as a resonance state in the $N\eta_c$ and $J/\psi p$ scattering process.

For the $IJ^P = \frac{1}{2} \frac{3}{2}^-$ system, the single channel calculation shows that $\Sigma_c D^*$, $\Sigma_c^* D$ and $\Sigma_c^* D^*$ are all bound. A bound state is also obtained with the energy of 4351.5 \sim 4359.8 (MeV) by the channel-coupling calculation. From

TABLE II: The Masses (in MeV) of the charmed and bottom baryons and mesons obtained from QDCSM. Experimental values are taken from the Particle Data Group (PDG) [20].

	Σ_c	Σ_c^*	Λ_c	Ξ_c^*	Ξ_c	Ξ_c'	Ω_c	Ω_c^*
Expt.	2455	2520	2286	2645	2467	2575	2695	2770
QDCSM	2378	2404	2200	2552	2464	2533	2698	2709
	D	D^*	D_s	D_s^*	η_c	J/ψ		
Expt.	1864	2007	1968	2112	2980	3096		
QDCSM	1890	1924	2105	2119	3224	3227		
	Σ_b	Σ_b^*	Λ_b	Ξ_b	Ω_b	B	B^*	
Expt.	5811	5832	5619	5791	6071	5279	5325	
QDCSM	5808	5816	5618	5887	6130	5333	5344	

TABLE III: The channels calculated in this work.

$IJ^P = \frac{1}{2}\frac{1}{2}^-$	$\Lambda_c D$	$\Lambda_c D^*$	$\Sigma_c D$	$\Sigma_c D^*$	$\Sigma_c^* D^*$
$IJ^P = \frac{1}{2}\frac{3}{2}^-$	$\Lambda_c D^*$	$\Sigma_c D^*$	$\Sigma_c^* D$	$\Sigma_c^* D^*$	
$IJ^P = \frac{1}{2}\frac{5}{2}^-$	$\Sigma_c^* D^*$				
$IJ^P = \frac{3}{2}\frac{1}{2}^-$	$\Sigma_c D$	$\Sigma_c D^*$	$\Sigma_c^* D$		
$IJ^P = \frac{3}{2}\frac{3}{2}^-$	$\Sigma_c D^*$	$\Sigma_c^* D$	$\Sigma_c^* D^*$		
$IJ^P = \frac{3}{2}\frac{5}{2}^-$	$\Sigma_c^* D^*$				

Table V, we can see that the ratios of all channels are from about 7% to 60%, which means the channel-coupling effect can not be ignored here. Additionally, the main state of the $IJ^P = \frac{1}{2}\frac{3}{2}^-$ system is $\Sigma_c^* D$, with the ratio 55.0% \sim 59.6%. The mass of this state is close to the observed $P_c(4380)$. Therefore, it is shown that in our quark model calculation the $P_c(4380)$ is a mixed structure of $\Lambda_c D^*$, $\Sigma_c D^*$, $\Sigma_c^* D$, and $\Sigma_c^* D^*$ with quantum numbers $IJ^P = \frac{1}{2}\frac{3}{2}^-$, and the main channel is $\Sigma_c^* D$. However, this state can be coupled to $J/\psi p$, so more work should be done to check whether there is a resonance state in the $J/\psi p$ scattering process.

For the $IJ^P = \frac{1}{2}\frac{5}{2}^-$ system, it includes only one channel $\Sigma_c^* D^*$, with the mass of 4512.0 \sim 4516.9 (MeV), which is a little higher than that of $P_c(4450)$. However, it is still a candidate of $P_c(4450)$, because the $J/\psi p$ decay mode of $P_c(4450)$ can be naturally interpreted as the $\Sigma_c^* D^*$ of $IJ^P = \frac{1}{2}\frac{5}{2}^-$. The S -wave $\Sigma_c^* D^*$ decay to D -wave $N\eta_c$ and $J/\psi p$ only through the tensor interaction, so the decaying width is generally small, which can be used to explain why the width of $P_c(4450)$ is much narrower than that of $P_c(4380)$.

For all $I = \frac{3}{2}$ systems, we find there is no any bound state. This is reasonable, because attraction for the $J^P = \frac{1}{2}^-$ channel $\Sigma_c D^*$ is too small to make it bound, so as the channel $\Sigma_c^* D^*$. For other channels, the interactions are all repulsive as mentioned above, which lead to no bound states here.

In the previous discussion, the hidden-charm molecular

pentaquarks were investigated. We also extend the study to the hidden-bottom pentaquarks because of the heavy flavor symmetry. Here we take the value of $\mu_{bb} = 0.0001$. The numerical results are listed in Table VI and Table VII. The results are similar to the hidden-charm molecular pentaquarks. For the $IJ^P = \frac{1}{2}\frac{1}{2}^-$ system, there exists a bound state, the mass of which is 11069.4 MeV, and the main state of this system is $\Sigma_b B$. For the $IJ^P = \frac{1}{2}\frac{3}{2}^-$ system, there is also a bound state of 11085.7 MeV, with a mixed structure of $\Lambda_b B^*$, $\Sigma_b B^*$, $\Sigma_b^* B$ and $\Sigma_b^* B^*$, and the main channel is $\Sigma_b^* B$. For the $IJ^P = \frac{1}{2}\frac{5}{2}^-$ system, a bound state $\Sigma_b^* B^*$ is obtained, with the mass of 11142.9 MeV.

IV. SUMMARY

In summary, the two newly observed resonant states $P_c(4380)$ and $P_c(4450)$ are investigated by solving the RGM equation in the framework of QDCSM. Our results show that $P_c(4380)$ is a mixed structure of $\Lambda_c D^*$, $\Sigma_c D^*$, $\Sigma_c^* D$, and $\Sigma_c^* D^*$ with quantum numbers $IJ^P = \frac{1}{2}\frac{3}{2}^-$, and the main channel is $\Sigma_c^* D$; $P_c(4450)$ can be interpreted as the $\Sigma_c^* D^*$ state of $IJ^P = \frac{1}{2}\frac{5}{2}^-$. Besides, we also obtain another bound state with quantum numbers of $IJ^P = \frac{1}{2}\frac{1}{2}^-$ and a mass of 4286.4 \sim 4301.7 (MeV), and the main state of this system is $\Sigma_c D$. However, all these states can be coupled to open channels, and the channel coupling will shift the energy of the state. Therefore, a further work is needed to check whether these states can survive as a resonance state in the corresponding open channels scattering process. Moreover, in the present work the parity quantum numbers of both $P_c(4380)$ and $P_c(4450)$ are negative. Although the present data of LHCb flavor the opposite parities, they also mentioned in their paper that the same parities were not excluded [8].

Besides the above calculation, we also extend our formalism to the hidden-bottom pentaquarks. The results are similar to the hidden-charm molecular pentaquarks. There exists a $IJ^P = \frac{1}{2}\frac{1}{2}^-$ bound state $\Sigma_b B$ with the mass of 11069.4 (MeV); a $IJ^P = \frac{1}{2}\frac{3}{2}^-$ bound state of 11085.7 (MeV) which can be considered as the partner of $P_c(4380)$, with the main channel $\Sigma_b^* B$; and a $IJ^P = \frac{1}{2}\frac{5}{2}^-$ bound state $\Sigma_b^* B^*$ of 11142.9 (MeV) which can be considered as the partner of $P_c(4450)$. These partners of $P_c(4380)$ and $P_c(4450)$ are worth searching in the future experiment.

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TABLE IV: The binding energy (in MeV) of the hidden-charm molecular pentaquarks of $I = \frac{1}{2}$.

	$J^P = \frac{1}{2}^-$						$J^P = \frac{3}{2}^-$					$J^P = \frac{5}{2}^-$
Channel	$\Lambda_c D$	$\Lambda_c D^*$	$\Sigma_c D$	$\Sigma_c D^*$	$\Sigma_c^* D^*$	$5cc.$	$\Lambda_c D^*$	$\Sigma_c D^*$	$\Sigma_c^* D$	$\Sigma_c^* D^*$	$4cc.$	$\Sigma_c^* D^*$
$\mu_{cc} = 0.01$	ub	ub	-18.1	-20.6	-23.9	-32.6	ub	-15.8	-17.2	-16.5	-32.5	-15.0
$\mu_{cc} = 0.001$	ub	ub	-14.9	-18.9	-22.5	-25.7	ub	-10.8	-14.2	-14.5	-30.7	-10.2
$\mu_{cc} = 0.0001$	ub	ub	-12.9	-17.9	-21.4	-17.3	ub	-10.5	-12.1	-12.9	-24.2	-10.1

TABLE V: The mass (in MeV) of the hidden-charm molecular pentaquarks of $I = \frac{1}{2}$ and the ratios (in %) of all channels.

	$J^P = \frac{1}{2}^-$						$J^P = \frac{3}{2}^-$					$J^P = \frac{5}{2}^-$	
	$M_{5cc.}$	$\Lambda_c D$	$\Lambda_c D^*$	$\Sigma_c D$	$\Sigma_c D^*$	$\Sigma_c^* D^*$	$M_{4cc.}$	$\Lambda_c D^*$	$\Sigma_c D^*$	$\Sigma_c^* D$	$\Sigma_c^* D^*$	$M_{1cc.}$	$\Sigma_c^* D^*$
$\mu_{cc} = 0.01$	4286.4	0.4	8.7	74.6	11.5	4.7	4351.5	12.8	12.1	57.9	17.2	4512.0	100.0
$\mu_{cc} = 0.001$	4293.3	0.4	6.1	82.0	7.2	4.3	4353.3	14.9	7.5	55.0	22.6	4516.8	100.0
$\mu_{cc} = 0.0001$	4301.7	0.8	5.0	74.3	10.1	9.7	4359.8	13.3	7.6	59.6	19.5	4516.9	100.0

TABLE VI: The binding energy (in MeV) of the hidden-bottom molecular pentaquarks of $I = \frac{1}{2}$.

	$J^P = \frac{1}{2}^-$						$J^P = \frac{3}{2}^-$					$J^P = \frac{5}{2}^-$
Channel	$\Lambda_b B$	$\Lambda_b B^*$	$\Sigma_b B$	$\Sigma_b B^*$	$\Sigma_b^* B^*$	$5cc.$	$\Lambda_b B^*$	$\Sigma_b B^*$	$\Sigma_b^* B$	$\Sigma_b^* B^*$	$4cc.$	$\Sigma_b^* B^*$
$\mu_{bb} = 0.0001$	ub	ub	-15.1	-20.5	-23.5	-20.6	ub	-13.7	-14.9	-16.4	-25.3	-14.1

TABLE VII: The mass (in MeV) of the hidden-bottom molecular pentaquarks of $I = \frac{1}{2}$ and the ratios (in %) of all channels.

	$J^P = \frac{1}{2}^-$						$J^P = \frac{3}{2}^-$					$J^P = \frac{5}{2}^-$	
	$M_{5cc.}$	$\Lambda_b B$	$\Lambda_b B^*$	$\Sigma_b B$	$\Sigma_b B^*$	$\Sigma_b^* B^*$	$M_{4cc.}$	$\Lambda_b B^*$	$\Sigma_b B^*$	$\Sigma_b^* B$	$\Sigma_b^* B^*$	$M_{1cc.}$	$\Sigma_b^* B^*$
$\mu_{bb} = 0.0001$	11069.4	0.4	4.9	73.4	11.8	9.5	11085.7	11.6	8.0	59.8	20.6	11142.9	100.0

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